Value of Weather Information: A Descriptive Study of the Fruit-Frost Problem

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Abstract

This paper reports some results of a descriptive study of the value of weather information used by fruit growers in the Yakima Valley of central Washington to decide when to protect their orchards against freezing temperatures. Specifically, the study provides data concerning the decision-making procedures of individual orchardists, the growers' use of weather information including frost (i.e., minimum temperature) forecasts, and the dimensions of the value of such forecasts.

Results from the descriptive study regarding the orchardists' information-processing and decision-making procedures are compared with the procedures included in a previous prescriptive study of the fruit-frost problem in the same geographical area (Katz *et al.*, 1982). The prescriptive study employed a dynamic decision-making model and yielded estimates of the economic value of frost forecasts under the assumption (*inter alia*) that the orchardists' decisions were based solely on these forecasts. On the other hand, the descriptive study with which the current paper is primarily concerned indicates that growers use temperature and dew point observations available after the frost forecast has been issued, as well as the frost forecasts themselves, to make frost protection decisions. Furthermore, while the results of the descriptive study show that the grower makes a series of decisions to protect or not to protect during the night, the model assumed that an irreversible commitment is made early in the night. The results of an initial effort to modify the original prescriptive model in accordance with the descriptive findings to obtain more realistic estimates of the value of frost forecasts also are reported in this paper.

Some implications of this study for the further development of prescriptive models of the decision-making process in the fruit-frost context and in other weather-information-sensitive contexts are discussed.

1. Introduction

In a recent paper, Katz *et al.* (1982) (hereafter referred to as simply KMW) used a dynamic decision-making model to investigate the economic value of frost (i.e., minimum temperature) forecasts to orchardists in the Yakima Valley of central Washington. The model allowed KMW to make hypothetical changes in the accuracy of current minimum temperature forecasts in order to determine the nature of the relationship between the quality and value of information in the fruit-frost decision-making process. The optimal strategies for the decision maker and the value-of-information estimates obtained from such a model are prescriptive in nature. That is, the strategies indicate the way an orchardist should behave in order to maximize expected payoff, given the structure of the model and the assumptions on which it is based.

Strategies actually used in practice may differ from those prescribed by the model, both because a model seldom faithfully reproduces all of the detailed structure in any real-world decision-making problem and because decision makers do not necessarily behave in a way that maximizes expected payoff. Therefore, it also is desirable to undertake a descriptive study of the fruit-frost problem, to determine how orchardists actually make decisions regarding frost protection. The primary purpose of this paper is to report the results of such a descriptive study in the Yakima Valley. In addition to providing a detailed description of orchardists' decision-making procedures, the paper identifies several significant dimensions of the value of forecasts in this context. The results of the descriptive study have implications for prescriptive modeling of the fruit-frost problem, and we present some results of an initial effort to modify the original prescriptive model to take such results into account in assessing the value of the frost forecasts.

The prescriptive and descriptive approaches to analyzing decision-making situations, including the assessment of the value of information, are discussed briefly in Section 2. Section 3 summarizes the primary results of this descriptive study. After a brief introduction to the fruit-frost problem, this section outlines the methods used in the study and describes the results of a series of interviews with orchardists in the Yakima Valley and the contents of frost protection records maintained by these fruit growers in 1982. The use and value of weather information in the context of the fruit-frost problem is discussed from a descriptive viewpoint in Section 4, with particular reference to the orchardists' decision-making process and the dimensions of the value of frost forecasts. Section 5 reports the results of an initial effort to take the results of this descriptive study into account in assessing the value of frost forecasts using a prescriptive model. A summary and conclusion are presented in Section 6.

2. Use and value of weather information: prescriptive and descriptive approaches

Two general approaches to the analysis and modeling of decision-making problems can be identified; namely, the prescriptive approach and the descriptive approach. The prescriptive approach is concerned with the manner in which the decision maker should process information and make deci-

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sions in order to maximize expected utility. This approach generally involves the formulation of a mathematical model of the problem, which in turn provides a basis for identifying optimal strategies and estimating the value of information. See Keeney (1982) for a recent review of the methodology involved in decision analysis, a particularly useful form of the prescriptive approach. The descriptive approach, on the other hand, is concerned with the manner in which the decision maker actually uses information and makes decisions. This approach involves a detailed analysis and description of the problem of interest, but it may not lead to the development of a formal decision-making model. Thus, the prescriptive and descriptive approaches have different objectives and are based on different methodologies. Nevertheless, they should be viewed as complementary modes of analysis, and a complete treatment of a decision-making problem would involve the use of both approaches.

Previous studies of the value of frost forecasts (Baquet *et al.*, 1976; Katz and Murphy, 1979; KMW, 1982) have employed a prescriptive approach. Under the assumption that the orchardist wants to maximize expected payoff (which is equivalent to maximizing expected utility under certain conditions), KMW estimated that the value of current frost forecasts for red delicious apples is $808 per acre (1977 dollars). Descriptive studies of frost-protection decision making have been conducted in Florida (Ward, 1974) and Utah (Jackson, 1974), but neither study explicitly considered the value of weather information. Such studies use interviews with decision makers and, if possible, observation of decision-making behavior and analysis of actual or hypothetical decisions to develop a description of the decision-making process. This description might consist of a list of the steps in the process, the information used, the major variables that influence the decision, and the important differences among decision makers. Descriptive studies also may result in formal quantitative models of the decision-making process (e.g., Hammond *et al.*, 1975).

3. Method and results of descriptive analysis

a. Background on fruit-frost problem in Yakima Valley

The Yakima Valley is an important fruit-growing region; the Bureau of Reclamation estimated the value of fruit production there at over $207 million in 1980 (Gilbery, 1982). Several nights each spring, fruit growers in the Yakima Valley face potentially disastrous crop losses due to frost. Fruits such as apples, cherries, pears, plums, peaches, and apricots are damaged by freezing of tissue (Ballard, 1978). Temperatures below freezing during sensitive stages of fruit development (March–May) have occurred an average of 36 times each year between 1945 and 1981, and some form of protection against frost has been required on an average of 16 nights each year (Graves and Lewis, 1981).

Growers use wind machines, sprinklers, and heaters to protect fruit crops against frost (Bagdonas *et al.*, 1978; Ballard, 1978). Wind machines, powered by truck engines, are in widespread use in the Yakima Valley. They work most effectively under inversion conditions by bringing warmer air from aloft down to the level of the trees and by keeping buds at the same temperature as the air around them. Oil and propane heaters are now used mainly as "borders" around orchards to be lit only when the protection provided by wind machines is insufficient. Some growers are removing heaters entirely because of high fuel costs and because the heaters obstruct sprayers and other equipment in the orchard. Both under- and over-tree sprinklers also are used extensively for frost protection. Sprinkling raises the temperature of the buds by means of the latent heat of fusion that is released when water freezes. The use of irrigation sprinklers for frost protection is cost effective, but it is limited by the availability of water. Both wind machines and sprinklers are easily started and are effective within a few minutes to half an hour. Starting an orchard full of heaters might require a crew and take an hour or more.

Each evening during the frost season, a fruit grower in the Yakima Valley must decide whether, and when, to take protective action against frost in the face of uncertainty concerning what the temperature will be later that night. To aid the orchardist in making this decision, the Yakima Weather Service Office of the National Weather Service (NWS) broadcasts minimum temperature forecasts for 25 stations throughout the valley. The role of those forecasts and other weather information in the growers' decision-making process was the focus of the descriptive study.

b. Method of data collection

A series of one-hour exploratory interviews was conducted just prior to the 1982 frost season. Twelve growers were interviewed by the first author in an open-ended format. The growers were asked to describe their frost-protection practices and the methods used to determine when to protect their crops.

Growers were identified through the agricultural extension agent and through referrals by other growers. The major divisions of the valley in Yakima county were represented. Orchard size varied from 42 to 320 acres, and all major fruit crops were included. The sample was diverse and included some of the largest and best-known orchards in the valley, as well as some smaller orchards. All currently used methods of frost protection were represented. Nine of the growers interviewed were asked to keep frost-protection records during the frost season. Eight growers returned detailed records.

c. Results of interviews

The frost-protection decision process described in the interviews varied little among the growers. This uniformity is not surprising since the professional growers have experienced the same type of hazard over many years, have access to essentially the same equipment, information, and options, and communicate with one another regularly. The growers' decision process can be described in seven steps:

1) Preparation of Equipment

The grower must determine that the protective equipment is ready to operate. For wind machines, fuel tanks must be

TABLE 1. Examples of critical temperature tables (from Ballard, 1978).

CRITICAL TEMPERATURE TABLES IN °F. WITH °C. IN PARENTHESES

APPLES*

Bud Development Stage	Silver Tip	Green Tip	Half-Inch Green	Tight Cluster	First Pink	Full Pink	First Bloom	Full Bloom	Post Bloom
Old Standard Temp.	—	—	22(-5.6)	26(-3.2)	26(-3.2)	—	27(-2.8)	28(-2.2)	29(-1.7)
Ave. Temp. 10% kill	10(-11.9)	18(-7.5)	22(-5.6)	25(-3.9)	27(-2.8)	27(-2.7)	28(-2.3)	27(-2.9)	28(-2.3)
Ave. Temp. 90% kill	0(-17.6)	4(-15.7)	11(-11.7)	18(-7.9)	21(-5.9)	24(-4.6)	25(-3.9)	24(-4.7)	26(-3.3)
Ave. Date (Prosser)	3/18	3/24	3/30	4/5	4/12	4/18	4/24	4/30	5/5

*For Red Delicious. Golden Delicious and Winesap approximately 1 degree hardier; Rome Beauty, 2 degrees hardier; except after petal fall, when all varieties are equally tender.

PEARS*

Bud Development Stage	Scales Separating	Blossom Buds Exposed	Tight Cluster	First White	Full White	First Bloom	Full Bloom	Post Bloom
Old Standard Temp.	—	25(-3.9)	25(-3.9)	27(-2.8)	28(-2.2)	—	28(-2.2)	30(-1.1)
Ave. Temp. 10% kill	16(-8.6)	19(-7.3)	23(-5.1)	24(-4.3)	26(-3.1)	26(-3.2)	27(-2.7)	27(-2.7)
Ave. Temp. 90% kill	0(-17.7)	4(-15.4)	9(-12.6)	15(-9.4)	20(-6.4)	20(-6.9)	23(-4.9)	25(-4.0)
Ave. Date (Prosser)	3/16	3/24	3/30	4/7	4/12	4/14	4/19	4/27

*For Bartlett. Anjou is similar in hardiness but may bloom earlier and therefore may be more tender than Bartlett at the same date.

CHERRIES*

Bud Development Stage	First Swelling	Side Green	Green Tip	Tight Cluster	Open Cluster	First White	First Bloom	Full Bloom	Post Bloom
Old Standard Temp.	—	—	—	—	—	28(-2.2)	—	28(-2.2)	30(-1.1)
Ave. Temp. 10% kill	12(-11.1)	22(-5.8)	25(-3.7)	26(-3.1)	27(-2.7)	27(-2.7)	27(-2.8)	28(-2.4)	28(-2.1)
Ave. Temp. 90% kill	1(-17.2)	8(-13.4)	13(-10.3)	18(-7.9)	21(-6.2)	23(-4.9)	25(-4.1)	25(-3.9)	26(-3.6)
Ave. Date (Prosser)	3/5	3/15	3/28	4/1	4/4	4/6	4/10	4/16	4/26

*For Bing. Lambert and Rainier approximately 1 to 2 degrees hardier through First White.

filled and the engine prepared and tested. For heaters, fuel tanks must be filled and the heaters checked. For sprinklers, lines and heads must be cleared. This preparation occurs prior to the frost season and at intervals during the season. On days when frost is expected, growers often will check their equipment to make sure it is in working order.

2) DETERMINATION OF CRITICAL TEMPERATURE

The critical temperature is the temperature below which bud damage will occur. It depends upon the type and variety of fruit, the stage of development, and recent weather conditions. Bud loss increases continuously as temperatures fall below the critical value (Proebsting and Mills, 1978), and most growers use the temperature at which 10% bud loss is expected as the critical temperature. All growers have critical temperature tables (Table 1) that indicate temperatures that will result in 10% and 90% bud kill within 30 min at the various developmental stages for different crops. Note that, for apples, the difference between a light 10% kill and a possibly disastrous 90% kill just before and after bloom is 3°F or less. Other crops exhibit similar sensitivity to small temperature changes.

At intervals during the frost season, bud hardiness tests are conducted at Washington State University's Irrigated Agricultural Research and Extension Center in Prosser, Washington, and the resulting critical temperatures are broadcast by radio. Some growers also have access to bud hardiness tests conducted by a local fruit company, but no growers test their own buds. Since growing conditions vary throughout the valley, the results of bud hardiness tests must be adjusted by the growers. They modify the given critical temperatures by a few degrees, depending on their observations of the stage of development of their own fruit crop and on the climate in their area in relation to the climate at Prosser. Some growers also adjust critical temperatures depending on recent weather. If an orchard has experienced a cold spell over a few days, the buds will be hardier. A recent warm spell means that the buds will be less hardy.

Since the tabled critical temperatures are averages, they must be adjusted by individual growers for conditions in their own orchards during a particular season. As a result, there is uncertainty about what temperatures the buds can withstand. Bud hardiness tests during the season reduce the uncertainty to some extent, but they are not orchard-specific.

Some growers make a conscious, deliberate determination of critical temperature at some time during the day. Others use a more informal, intuitive approach. All growers have a critical temperature in mind for their orchards as the evening begins.

3) Receipt of Forecast

All growers listen to the NWS minimum temperature forecast given between 7:00 and 8:00 pm each night. The forecast describes relevant weather conditions, predicts minimum temperatures that night for 25 stations distributed throughout the valley, and describes general conditions expected during the next few days. Particular attention is given to any changes expected during the night such as a cloud cover moving in or winds changing or dying out. Dew points at the Yakima Airport at 4:00 and 7:00 pm also are reported.

Experienced growers know which of the 25 forecast stations is most similar to their orchards (in terms of temperature conditions), and they generally can state how much warmer or colder, as a rule, their orchards are than that station. They then adjust the NWS forecast accordingly.

4) Use of Frost Alarm

All growers interviewed used frost alarms. These devices have sensors which are placed in the orchard or at a location that has temperatures similar to those in the orchard. An alarm, usually kept in the bedroom, is activated when the outside temperature reaches a preset level (usually a few degrees above the critical temperature). Most growers gave a specific rule of thumb for setting the alarm—for example, 2°F above the critical temperature—which might vary as the season progressed. Some orchardists indicated that if a cold night were expected, they might raise the setting slightly, but never more than 1°F.

5) Vigilance

When the frost alarm is activated, awakening the grower, a period of vigilance begins. The grower circulates through the orchards, making the rounds of strategically placed thermometers. Some growers have portable electronic thermometers for continuous temperature monitoring. They listen for NWS radio updates giving dew points and any changes in weather conditions. Often orchardists will report observations to the NWS and these reports (e.g., "cloud cover seen moving in over the west valley") are included in the broadcast updates.

Growers talk to each other during the vigilance period. Some orchardists have citizen-band radios, and often they will stop to talk as they pass each other in their vehicles. One grower reported maintaining a coffee pot for other growers during the night. A grower who sees that a neighbor is not awake usually will alert the neighbor to danger.

6) Decision to Protect

Starting a wind machine is virtually instantaneous if all equipment is in working order. Growers sometimes start the machines and leave them idling as temperatures drop. It takes about 5 min for the machines to create enough mixing of the air to be effective. The growers reported that they could get all their wind machines started in 15–30 min. Starting the sprinklers is even easier. The grower has only to turn a valve and, in most cases, start a pump. A few electric wind machines and some sprinklers are equipped with automatic switches or valves that start them at a preset temperature.

The growers reported initiating protection within a few degrees Fahrenheit of the critical temperature. This decision is related to the observed rate of temperature drop, the dew point, and the minimum temperature forecast. If the dew point is low, the night clear and still, and low temperatures expected, growers are prepared for a relatively rapid drop to low temperatures and will initiate protection sooner than they would if the dewpoint were high or a cloud cover were expected. However, because of the short lead time required to bring the protective equipment to full effectiveness, minor adjustments in the time that protection is initiated generally are sufficient.

The growers continue to monitor temperatures while protective equipment is operating, and if conditions improve, they will cease protecting. For some growers, protection is a sequential process involving a series of steps. They may decide to protect different areas at different times. If they have heaters, they may decide to use them in combination with wind machines when temperatures threaten to drop very low.

7) Damage Assessment

The morning after a frost, growers examine their trees to estimate the extent of damage. This survey provides feedback about the results of the previous night's activity. Since the grower knows the temperatures reached in the orchard, the bud kill can give a kind of hardiness test that may lead the grower to adjust critical temperatures for the next night. If no kill was experienced, the grower might be inclined to let temperatures drop a little lower before initiating protection on a subsequent night.

A light kill may be beneficial because it reduces the amount of thinning of buds required later in the spring. It is possible to experience substantial bud loss and still have a good harvest. The growers who use frost for thinning (a controversial practice) might let temperatures drop somewhat below the critical temperature if, late in the season, little bud loss had occurred. On the other hand, if the damage assessment showed the crop to be a total loss, the grower obviously would cease heating for the rest of the season. This use of "prior bud loss" in decision making is consistent with the dynamic decision-making model employed by KMW.

The process described above is used by all the growers interviewed. Table 2 summarizes the activities and the sources of information for the equipment preparation, critical temperature determination, frost alarm setting, and protection decision steps. Receipt of forecast, vigilance, and damage assessment steps are not included in Table 2 because these activities are information-gathering, not decision-making, steps.

TABLE 2. Decisions in frost protection.

Decision step	Activities requiring judgment	Time decisions made	Information sources
Preparation of equipment	Equipment checking, preparation, and maintenance	Hours to weeks before frost event	Climate Weather forecasts Other growers
Determination of critical temperature	Estimating critical temperatures for each crop & variety	During day before frost event	Critical temperature tables Bud hardiness tests Observations of bud stage Recent weather Previous night's consequences Other growers
Use of frost alarm	Setting temperature on frost alarm	Bedtime—hours before frost	Critical temperature estimates Frost forecast Observations of current weather
Decision to protect	Operating protective equipment	Minutes to hours before frost	Critical temperature Prior bud loss Frost forecast Current weather (temperature, dew point, sky cover, winds) Observations of weather trends Reports from other growers

d. Results from frost protection records

The instructions for maintaining the frost protection records appear in the Appendix, and an example of one page of those records is presented in Fig. 1. Although all growers use the same general decision process, comparison of the frost-protection records kept by the eight orchardists during the 1982 frost season (approximately 15 March to 8 May) reveals differences among the orchardists with regard to the amount of protection used (Table 3) and with regard to critical temperatures, frost alarm settings, and protection initiation temperature (Table 4). Table 5 illustrates marked differences among growers on two of the coldest nights of the season. These differences can be attributed to a number of factors:

1) Some growers are more "risk averse" than others (Conklin *et al.*, 1977). According to decision theory, risk aversion is measured by a person's willingness to pay a premium, similar to an insurance premium, to avoid risk (Raiffa, 1968). For the growers, the premium is paid in increased heating costs. The differences among growers could partially result from differences in risk aversion, but other important variables make it difficult to isolate this factor.
2) Growers may rely on different types or sources of information in making their judgments, or give different weights to various types of information.
3) Different weather conditions exist in different parts of the valley, and these differences affect both bud hardiness and the minimum temperatures. The elevation, slope, and general topography of the orchards vary, and these factors influence the need for heating (Jackson, 1974). For example, growers A and B are in the hills of the northern valley where little frost protection generally is required, whereas growers E and F are in an area that has required much more protection historically.
4) Different protective equipment (wind machines, sprinklers, or heaters) has different heating and start-up characteristics and therefore requires a different strategy (Bagdonas *et al.*, 1978). For example, grower H uses only sprinklers, equipment that is relatively inexpensive to operate. This factor may account for his high total hours of protection.
5) Different fruits and varieties vary with respect to hardiness. Most growers have a mixture of varieties that must be considered in the protective strategy.
6) Buds must be thinned in order to help the fruit to mature effectively. Growers differ on whether to allow frost to do some of this thinning.
7) Some of the variability in any set of data can be due to measurement error. Growers may have made judgmental errors or errors in recording data on the forms.

The large number of variables that might account for differences among growers and the small amount of data collected in this study preclude an analysis of the relative importance of the variables in explaining the differences. An interesting question, but one that cannot be addressed with these data, is whether the different growers' strategies are appropriate for the conditions in their particular orchards. In other words, do growers use optimal decision-making strategies, given the information available? Or are some growers being overly conservative, protecting unnecessarily and thereby increasing costs, or being unduly reckless, avoiding heating costs at the risk of crop injury?

The growers' strategies apparently were effective in protecting crops for the 1982 season. In spite of a number of cold, potentially damaging nights during the season, only one grower reported significant crop losses in protected areas. That loss, in a cherry orchard, occurred because temperatures were so low that heaters were not effective. The data are insufficient to determine whether the growers' successes were gained at the expense of unnecessary heating.

Date	* Critical Temperature	* Frost Alarm Setting	Protection Temperature	Dewpoint	Time Began Protection	Time Ended Protection	Type of Protection Used: Wind Machines	Overtree Sprinklers	Undertree Sprinklers	Heaters	No. of Acres Protected	* Minimum Temperature	* Percent Bud Loss	* Comments (Use back of sheet if necessary)
3-16	22°	26°	22°		5:30 AM	7:00	✓ 3+				80	20 *		* The minimum temperature was in another orchard. At this early date in the season mostly worried about protecting stone fruits. + no. of machines used
3-19	24	27°	25	22°	5:00 AM	7:00	✓ 4				100	23		Again coldest temp. in another orchard (apple) Protecting: peaches nectarines cherries
3-20	25°	28°	25°	25°	4:30 AM	7:30	✓ 5				120	20		same cold apple orchard — protecting same as above —
3-22	26°P * 26°C 22°A	32°	26°	25°	didn't							27 +	—	* P = peaches C = cherries A = apples + cold temperature seen in two blocks nectarines & peaches
3-23	26P 27C 22A	33°	26°	*	didn't							27		* radio broken — don't know.
3-24	26 P 27 C 22 A	33°	26°	21°	1:30 AM * 4:30	6:30	✓ 3				80	26° +		* started one machine @ 1:30 shut it down at 3:00 started 3 machines again at 4:30 + 26° temp was in a different orchard.
3-28	27 P 27C 25A	33°	27° * 25°A	23°	3:30 AM	6:30	✓ 2				60	27°		* We began blossom thinning peaches thus can't afford to lose any — from now on we will protect for 100% set with minimum starting temp. @ 28° going to 30° later. Also first time apples advanced enough to worry
3-29	28 P 27C 25A	33°	28° 25°A	22°	3:00 AM	6:15	✓ 6				128	25°		This is the first time we had machines working on the other ranch (one machine covering about 8 A) 25° minimum was recorded in apple orchard

* Record these items even if you decide not to protect

FIG. 1. Sample page from a frost protection record form.

TABLE 3. Comparison of protection used by eight growers.

Grower	Number of nights of protection during season	Types of equipment used	Dates of protection		Hours of protection			
			First	Last	Total	Daily minimum	Daily median	Daily maximum
A	5	WS	4/17	4/28	21.5	1.0	5.0	6.5
B	4	W	4/18	4/29	13.0	1.5	2.5	7.0
C	17	WS	4/7	5/5	75.0	1.5	4.5	9.5
D	19	WHS	3/15	5/5	74.0	1.0	4.0	10.0
E	20	WH	3/16	5/8	91.0	1.5	4.5	9.0
F	21	WH	3/16	5/7	96.5	1.0	3.5	8.0
G	10	WS	4/3	4/21	44.5	1.5	4.0	8.5
H	15	S	3/28	5/3	127.5	5.5	8.5	12.0
Median	16				74.5	1.5	4.5	9.0

Equipment Code: W = wind machines
S = over- or under-tree sprinklers
H = heaters (used on borders with wind machines)

4. Use and value of frost forecasts from a descriptive viewpoint

a. Description of growers' use of weather information

The growers described a complex, dynamic, and continuous information-gathering and decision-making process. During the period of vigilance prompted by the frost alarm, each moment's decision to initiate, or terminate, protection is based on new information and on the outcomes of past decisions. This process represents a highly evolved system of hazard protection that is possible because: 1) the protective equipment (generally wind machines or sprinklers) quickly can be brought to full effectiveness; 2) critical variables such as temperature and dewpoint can be monitored continuously and accurately; and 3) both the cost of protection and the value of the threatened crop make it worth the grower's effort to maintain a vigil throughout the night.

Figure 2 compares the nightly decision process described by the growers with the process assumed in the prescriptive models of the frost protection decision. As the figure illustrates, one difference between the growers' process and the model is the information gathered by the orchardists *after* the NWS forecast is broadcast. This information is obtained from the frost alarm sensor, the grower's observations during the period of vigilance, and updates of dew point and other weather conditions broadcast through the night. In effect, the growers are making continuously updated "nowcasts" for the next 20-30 min based on current, orchard-specific information, whereas the model relies on a single forecast for the entire night. Furthermore, while the grower can decide whether to protect at any time during the night, the model assumes that an irreversible commitment is made at one decision point. To estimate more realistically the value of the forecasts to the grower, a prescriptive model should attempt to take into account both the information available to the grower after the forecast is made and the grower's ability to make the decision to protect at any time during the night.

b. Dimensions of value of frost forecasts

The descriptive study cannot provide a dollar estimate of the value of the forecasts, but it does suggest some important factors to be considered in the assessment of value. The potential value of the forecasts appears to lie in three areas: avoidance

TABLE 4. Summary of frost protection forms for eight growers

Grower	Critical temperature for apples* (°F) Minimum	Median	Maximum	Degrees frost alarm set above critical temperature (°F) Minimum	Median	Maximum	Degrees above critical temperature that protection began (°F) Minimum	Median	Maximum
A	24	24	28	4	4	4	0	1	2
B	22	22	27	3	3.5	4	−1	1	2
C	22	24	30	1	2	4	−1	1	2
D	27	30	30	0	1	3	−1	0	4
E	19	28	28	2	3	6	1	1	3
F	22	27	28	3	6	8	−1	0	3
G	26	28	28	4	4	6	3	3	4
H	27	29	29	4	5	5	3	3.5	4
Median	23	27.5	28	3	4	4.5	−0.5	1	3

* These depend on stage of development and variety. Since critical temperatures were only recorded on cold nights, the dates of protection (Table 3) account for much of the variation among growers seen here.

TABLE 5. Comparison of growers on the nights of 19 and 20 April.

Grower	Day	Critical temperatures for apples (°F)	Temperatures when protection began (°F)	Dew point (°F)	Time protection began	Time protection ended	Minimum temperature (°F)	Bud loss (%)
A	19	24	25	16	11:30 pm	6:00 am	20	10
	20	24	25	23	1:00 am	6:00 am	24	0
B	19	22	Did not protect					
	20	22	23	24	10:30 pm	5:15 am	23	0
C	19	24	26	19	12:00 am	7:30 am	24	0
	20	25	26	20	4:00 am	6:30 am	26	0
D	19	30	30	18	1:30 am	6:30 am	29	0
	20	30	31	16	11:00 pm	6:30 am	30	0
E	19	28	30	20	1:15 am	5:45 am	28	0
	20	28	30	17	9:30 pm	6:30 am	27	10
F	19	28	30	17	12:30 am	6:15 am	27	0
	20	28	30	22	10:00 pm	6:00 am	27	0
G	19	28	31	19	1:45 am	6:15 am	27	0
	20	28	31	17	10:00 pm	6:15 am	28	0
H	19	29	32	20	12:30 am	8:30 am	27	0
	20	29	32	21	1:30 am	7:00 am	30	0

of crop damage, reduction of heating costs, and psychological comfort.

1) Avoidance of Crop Damage

Crop damage could result if a temperature drop caught a grower by surprise. For example, one grower in this study reported a 20% bud loss due to a rapid drop in temperatures before his protective devices became effective. Forecasts can help prevent this loss by alerting the grower to the possibility of damaging temperatures. These forecasts are the primary source of information available to the grower about weather

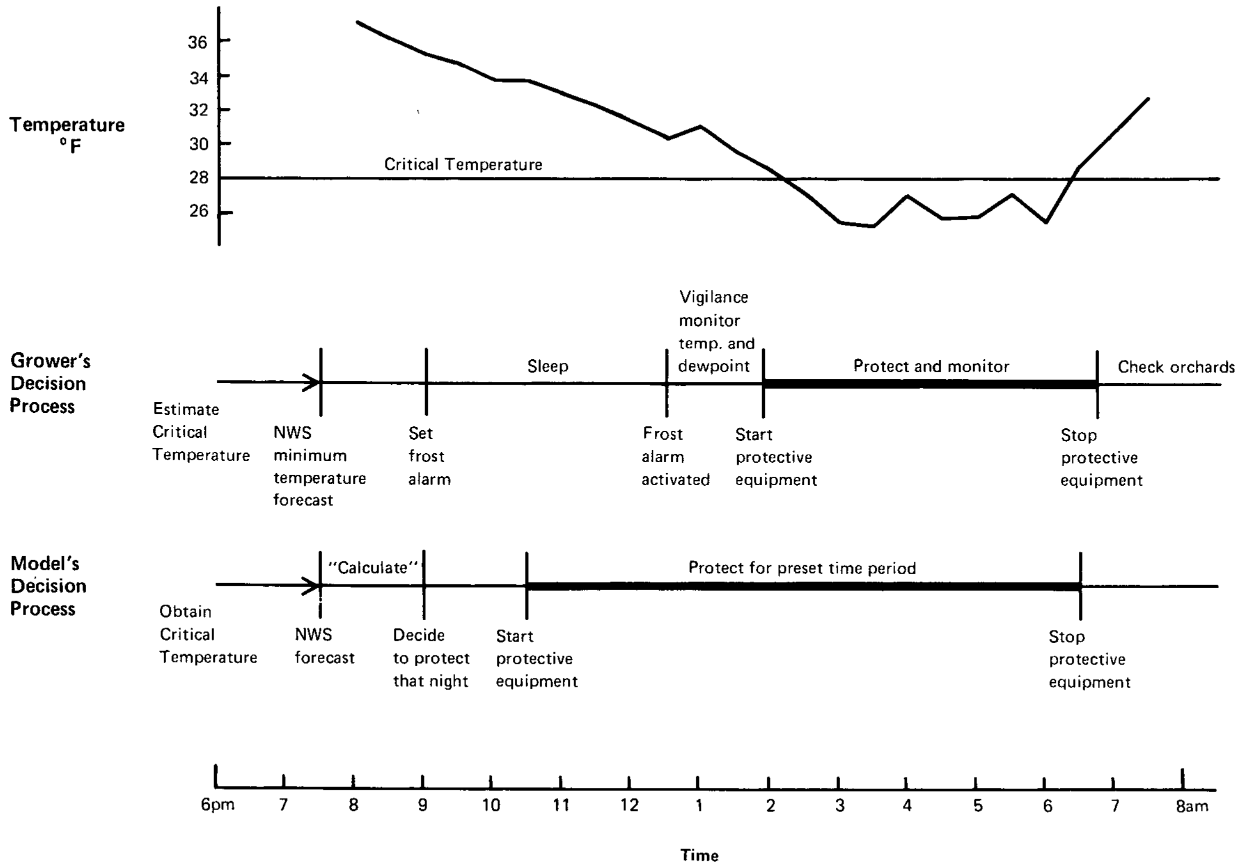

FIG. 2. Comparison of grower's and model's decision-making process.

changes expected during the night. However, forecasts are not the growers' only defense against surprises. Because of the general alertness of the competent growers, their ability to start protecting crops quickly in the event of a sudden temperature drop, and the warning systems provided by frost alarms, all-night radio updates, and networks of neighbors, it seems unlikely that such growers would be caught by surprise very often even without the forecasts. Nevertheless, forecasts can increase awareness of the possibility of a rapid temperature drop.

Another possible cause of crop damage would be equipment failure. One grower in this study reported trouble starting a wind machine and, later in the season, one machine stopped running altogether during a cold night. This danger can be reduced by adequate preparation—filling fuel tanks, clearing sprinkler heads, etc. Such preparation is part of a grower's general routine, but frost forecasts, particularly early in the season after the equipment has been idle for the winter, can alert the growers to the need to check their equipment.

Crop damage generally would result if orchard temperatures dropped below the effective range of the heating equipment and stayed there. In this event, some damage is unavoidable, and even perfect forecasts would not eliminate this damage completely. On a very cold night when total crop loss is unavoidable, an accurate forecast could save growers the cost of heating. However, several growers indicated that they would heat anyway on such a night, as many did on "Black Thursday" in 1968, because they could not stand by without trying to prevent the destruction of their crop. Ward (1974) reports similar feelings among Florida growers.

In summary, forecasts play a role in alerting growers to the possibility of crop damage so that they can be prepared to protect their crops if needed. However, forecasts are not the only source of information that serves this purpose. Additional sources of information in the system help the grower, making it difficult to estimate the marginal value of the forecasts.

2) HEATING COSTS

Forecasts alert the growers to the expected minimum temperature and to other weather changes expected during the night. This information may allow the growers to make better short-term predictions and to initiate heating later, or stop heating earlier, than they would without forecasts. For example, if the forecast predicts that a cloud cover will move in during the night, the grower may be less concerned about a drop in temperature and may postpone heating. If the cloud cover appears as predicted, the grower may not heat at all, thus avoiding an unnecessary cost.

Here, too, there are other sources of information to augment the forecasts. Dew point information (provided during the night by the NWS) is used as a short-term forecasting aid. Also, reports from other growers in different parts of the valley are broadcast over the NWS radio. Therefore, the impact of the weather forecast itself is difficult to isolate. Still, the forecast may well reduce heating costs by allowing the growers to protect crops for shorter periods of time than they would if no forecast were available. The costs of frost protection are low, however, relative to the value of the crop. Fagerlie and Folwell (1980) estimate the seasonal cost of wind machine operation at $32.60 per acre—about 1% of the $3376 average value of an acre of apples in 1980 (Gilbery, 1982).

3) PSYCHOLOGICAL COMFORT

Although the miminum temperature forecasts are only one piece of information that growers use in making decisions, the growers strongly support the NWS frost forecasting service. Fruit growers are players in a high-stakes game. Their concern about avoiding crop damage was evident throughout the interviews, and they work hard to protect their crops. According to decision theory, information has no economic value unless it has the potential to alter the decision maker's actions. To growers, however, information that reduces uncertainty about the outcome of actions that were already planned can be valuable. For example, a grower who is forced to be away from the orchards for a night (leaving someone else to watch over the crop) might ascribe value to a forecast for that night, even though no action could possibly be taken based on the forecast. The psychological implications of risk have been of major interest in the field of risk assessment (e.g., Fischhoff *et al.*, 1981). Finsterbusch (1982) describes the importance of psychological impact of proposed actions and some approaches to assessing it. While the forecasts seem to have psychological value for the growers, such a non-economic value is difficult to quantify and it is not clear what importance should be attached to such value in a calculation of the benefits of forecasts to society as a whole.

5. Economic value of frost forecasts from a prescriptive viewpoint: A revised estimate

KMW assumed, for simplicity, that the only current information available to orchardists during the evening is the NWS minimum temperature forecast. The descriptive results reported in Sections 3 and 4 show that current weather information obtained after the dissemination of the forecast is used by the growers. More realistic estimates of the value of the forecasts to growers would be obtained if the availability of this current weather information were explicitly taken into account. This section presents a revised estimate of the value of the forecasts and describes the method used to obtain this estimate.

Observations of temperature and dew point at both 10:00 pm and 1:00 am for the Yakima key station during the 1957–76 frost seasons were obtained. Since the NWS minimum temperature forecast for the Yakima key station is issued by 8:00 pm, these observational data would not become available to the orchardist until after receipt of the forecast. On the other hand, since protective action generally is initiated after midnight, the 1:00 am information is reasonably representative of the information that the grower would have at the time that the protective decision is made. Observations of temperature and dew point at 7:00 pm also were considered, so that the change in temperature and the change in dew point over the previous three hours could be used as predictors of minimum temperature.

Predictive equations were developed by means of multiple regression analysis. The temperature and dew point observations, as well as the NWS minimum temperature forecast, were employed as independent variables to estimate the dependent variable—observed minimum temperature for the Yakima key station. Surprisingly, no combination of the additional observations was able to improve upon the accuracy of the NWS forecasts alone. Here accuracy is measured in terms of the conditional standard deviation of observed minimum temperature given the prediction based on the regression equation (i.e., the so-called root mean square error of the regression equation).

It should be emphasized that this result, regarding the apparent lack of usefulness of current observations of temperature and dew point, applies only to the problem of predicting minimum temperature. In practice, orchardists would want to know the time of occurrence and duration of certain temperature events (e.g., the event of the temperature being below a certain critical level). These considerations, however, are not treated in the current version of the prescriptive decision-making model.

The value of the NWS minimum temperature forecasts is measured relative to climatology by KMW. If it is assumed that other information is available to the orchardist, then the value of the minimum temperature forecasts should be measured relative to the combination of climatology and this additional information. To realize this objective, observed minimum temperature was regressed on various combinations of temperature and dew point observations. The NWS minimum temperature forecasts were excluded from these regressions. Two independent variables—1:00 am temperature and dew point—produced predictions virtually as accurate or more accurate than models involving all six independent variables. The conditional standard deviation of observed minimum temperature given the prediction based on 1:00 am temperature and dew point is approximately 5.9°F, somewhat smaller than the climatological standard deviation of about 6.7°F.

For red delicious apples in the Yakima Valley, the dynamic decision-making model was evaluated for the situation in which the observations of 1:00 am temperature and dew point, but not the NWS forecasts, are available to the orchardist. The total expected expense in this case is approximately \$1676 per acre (in terms of dollars for the year 1977). This total expected expense is about \$45 less than that for climatological information alone. Consequently, the estimated value for minimum temperature forecasts given in KMW would be reduced by roughly \$45 if the availability of 1:00 am or earlier meteorological observations were taken into account. This result indicates that the value of the minimum temperature forecasts is at least slightly lower than previously estimated. If the additional information assumed to become available to the grower after the receipt of the forecast is extended to include nearly continuous temperature readings and hourly dew point updates, rather than just the 10:00 pm and 1:00 am readings, then the value of the forecasts should be further reduced. But the analysis reported here suggests that the reduction may not be large.

In Section 4 we noted that the prescriptive model does not reflect the grower's ability to make a series of protective decisions each night. The model assumes that an irreversible decision is made at a single time during the night. If the opportunity to make a series of decisions were incorporated into the model, then the value of the forecasts, relative to climatology and current weather, would surely change. Estimating the magnitude of this change would require a structural modification of the model. Such a modification was beyond the scope of this study.

6. Summary and conclusion

In this paper we have presented the results of a descriptive study of the value of weather information to orchardists in the Yakima Valley of central Washington. The descriptive study showed that the growers' frost protection decision process involves not only a decision about whether to protect crops on a given night, but also decisions about when to initiate protection and how long to maintain protection. The evening minimum temperature forecast is broadcast near the beginning of a continuous process of information acquisition and processing conducted at first mechanically (by the frost alarm sensor) and then by the grower. Because of the complexity of the decision process and the number of variables involved, it is difficult to isolate and quantify the value of the minimum temperature forecasts. The potential value of the forecasts in preventing catastrophic losses, reducing heating costs, and providing psychological comfort was discussed qualitatively.

In order to provide a refined estimate of forecast value, the prescriptive model described by KMW was revised to include temperature and dew point information obtained after the minimum temperature forecast was broadcast. The effect of this additional information was a small reduction in the previous estimate of the value of the forecasts. Modifying the model to provide for multiple decision points during the night would be expected to have an impact on the value of the forecasts.

The features of the growers' decision process that are relevant to the economic value of the forecasts could, in principle, be represented in a prescriptive, decision-analytic framework. The growers' decision-making procedures could, for example, be modeled as a series of decisions to initiate (or terminate) protection based on the growers' utilities and the probability distribution over minimum orchard temperatures expected between the time of the decision and the time that protection could reach full effectiveness. The probability distribution could be based on the minimum temperature forecast and all the prior information available at the time of the decision. Of course, the practical problems of formulating such a model would be formidable.

Fruit-frost protection is just one example of a dynamic process in which weather forecasts are used along with other types of information to make decisions. Forest fire management (Radloff and Yancik, 1983) and irrigation scheduling (Rhenals and Bras, 1981) are other examples of highly dynamic processes that are weather-information sensitive. What varies from one decision problem to another is the lead-time required to take effective action (Howe and Cochrane, 1976), the ability to monitor current information and to observe the results of previous decisions, and the reversibility of the action once taken.

As this study illustrates, it can be difficult to assess the value of weather forecasts when they are used together with other information in a dynamic process. However, a combination of descriptive studies and prescriptive models may prove useful in investigating the value of forecasts in such situations. Descriptive studies can establish a framework for the development of prescriptive models that realistically represent both the decision maker's constraints and opportunities. The models then can be used to investigate quantitatively both the value of improved forecasts and the value of improved use of forecasts.

Appendix. National Center for Atmospheric Research Frost Protection Record

Instructions:

Please keep records for each night that you are awake during the frost season, whether or not you actually use protection. Protection includes wind machines, sprinklers, heaters or any other device you use to heat. If you don't actually use any protection during a night, record only the items marked "*" on that night. Below is an explanation of the terms used on the form.

*1. *Critical Temperature.* This is the temperature which you use as a guideline for bud hardiness. It is the temperature that you want to avoid because bud damage will occur.
*2. *Frost Alarm Setting.* Record the setting on your frost alarm.
3. *Protection Temperature.* This is the temperature reached in the orchard just before you began heating. Record the last temperature reading you took before initiating protection.
4. *Dewpoint.* Record the last dewpoint reading you received before you began protecting.
5. *Time Protection Began and Ended.* Record, as nearly as possible, the time you first began to protect, and the time that all heating was stopped.
6. *Type of Protection.* Check each method of protection used during the night, even if a method was used for only part of the night.
7. *Number of Acres.* Record the total number of acres protected by any method during the night.
*8. *Minimum Temperature.* Record the minimum temperature you observed during the night. If you have a minimum temperature thermometer, its reading should be recorded.
*9. *Percent Bud Loss.* Estimate the percent bud loss the following day. If possible, the bud loss should be observed at about eye level on the trees near a properly sheltered minimum temperature thermometer or near the location where you observed the lowest temperature.
*10. *Comments.* Your comments and observations during the night and the next morning will be extremely helpful. Anything that you feel is important should be noted, but we are particularly interested in the following:

    Any unusual weather conditions in your area;
    Any equipment problems you experienced (e.g., wind machine malfunction);
    Any other special circumstances that occurred during the night that might have influenced your decisions.

It is important that these records be as accurate as possible, but we do not expect you to make observations that you would not make anyway. The purpose is merely to obtain a record of your decisions and the information that was available to you. It is helpful, or course, to record your observations as soon as possible.

If any of the numbers you record depend upon the type of fruit or the area of your orchard, then record the numbers that apply to *apples* (or your major crop if other than apples) and to the *coldest part of your orchard,* if your orchard temperature varies.

* Record these items even if you decide not to protect.

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announcements *(continued from page 125)*

June through 17 August 1984. Postdoctoral to mid-career scientists, engineers, and other appropriate professionals are encouraged to apply. The awards will be announced prior to the end of April 1984.

Environmental Science and Engineering Fellows will work as special research consultants within the Environmental Protection Agency's (EPA) Office of Research and Development in Washington, D.C. Guided by AAAS and EPA, they will select their research tasks and approach prior to coming to Washington for the 10–week period. The AAAS will manage the selection process, arrange a carefully structured orientation program, and coordinate frequent seminars throughout the 10–week period for the Fellows. The Program will end with oral and written presentations by the Fellows on their assigned research projects.

Each 1984 Fellow will receive a taxable stipend of $575.00 per week; a nominal additional amount is available for temporary relocation expenses and travel in connection with the fellowship.

The purpose of the fellowship program is to assist EPA's research and development planning and policy making by developing processes and methods for indentifying future environmental problems and opportunities; communicating the results of strategic assessments and studies to a wide range of individuals, groups, and agencies in ways that are meaningful and practical; and providing both outreach to the professional community concerned with environmental assessment and additional education of that community of the policy dimensions of such work.

Prospective Fellows are expected to show exceptional competence in a relevant professional area, have a broad professional background, and have a strong interest and some experience in applying scientific or other professional knowledge toward the identification and assessment of future environmental problems. Applicants should have backgrounds in the physical, biological, or behavioral sciences or any field of engineering, or other relevant professional field.

Applications must be received by *1 March 1984* and should include: 1) a letter from the candidate indicating a desire to apply; 2) two letters of reference which include addresses and telephone numbers of respondents; 3) a statement from the candidate about his/her qualifications for the fellowship and his/her career goals; and 4) a full curriculum vitae.

The letter from the candidate should indicate availability for a possible interview during early April. It would also be helpful if the applicant could state how they first learned about the program.

References should be people who can discuss, not only the candidate's professional competence and his/her ability to do environmental policy research, but also other aspects or interests that would make the applicant particularly qualified to serve as an Environmental Science and Engineering Fellow. Each reference letter should address: 1) the respondent's relationship to the candidate; 2) the technical accomplishments and relative standing of the candidate among his/her peers; 3) the candidate's ability to communicate both in writing and orally, and to interact productively with individuals and groups; 4) the candidate's maturity and judgmental ability; and 5) the candidate's professsional future.

The candidate's statement should not exceed 1000 words in length and should cover at least the following four areas: 1) why the fellowship is desired; 2) how the candidate is qualified; 3) given the choice, what issues the candidate would like to work on, why he/she would like to work on them, and what approach might be taken by the candidate in performing such research; and 4) what outcome of the experience is hoped for relative to the candidate's career goals.

Applications and reference letters should be sent to Patricia S. Curlin, Senior Program Associate, American Association for the Advancement of Science, 1776 Massachusetts Ave., NW, Washington, DC 20036.

Environmental specimen banks

The United States and the Federal Republic of Germany have been testing facilities for the long-term storage of biological and environmental specimens that can later be retrieved for chemical analysis, and researchers from both countries agree that full-scale, permanent installation of specimen banks can begin. The U.S.

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